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# STORAGE DEVICES
# for Communications

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# STORAGE DEVICES
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Improved communications systems are predicted upon devices in which the time scale is expanded and compressed as well as upon delay types. Equipment for attaining these conditions, including electrostatic storage tubes, delay lines and flip-flop circuits, is described

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STORAGE OF information takes place, in some form or other, in all communications systems, and is evidenced by the fact that the output of a system is a weighted response to the past of the input. It is known that the output of a system does not depend alone on the present value of the input, but is also influenced, to varying degrees, by the previous behavior of the input.

In general, the storage and weighting functions of a system are combined, and the storage is not clear-cut. It is not usually possible to point to a part of the system and say that it contains, in recoverable form, all input events that have occurred in an interval $T$ extending from the present into the past. Rather, the storage is distributed throughout the system, and the identity of individual input events is lost.

Recently, the need has developed for systems whose sole function is storage—systems that will retain all input events occurring in a particular interval, and from which the events can be individually recovered. Advances in the theory of communications have shown that an insight into many communications problems may be obtained through the use of such systems

**Much has been published during the last few years on the subject of new communications theory. Although it is theoretically true that systems can be designed to enhance signal-to-noise ratio or to conserve bandwidths in our diminishing radio channels, we have not yet attained the ultimate in equipment for the purpose.**

**Particularly to the non-communications type of reader this article will serve for orientation. Although the electronic circuitry of devices now a-building is not detailed, the gross outlines of the building blocks are described. —The Editors**
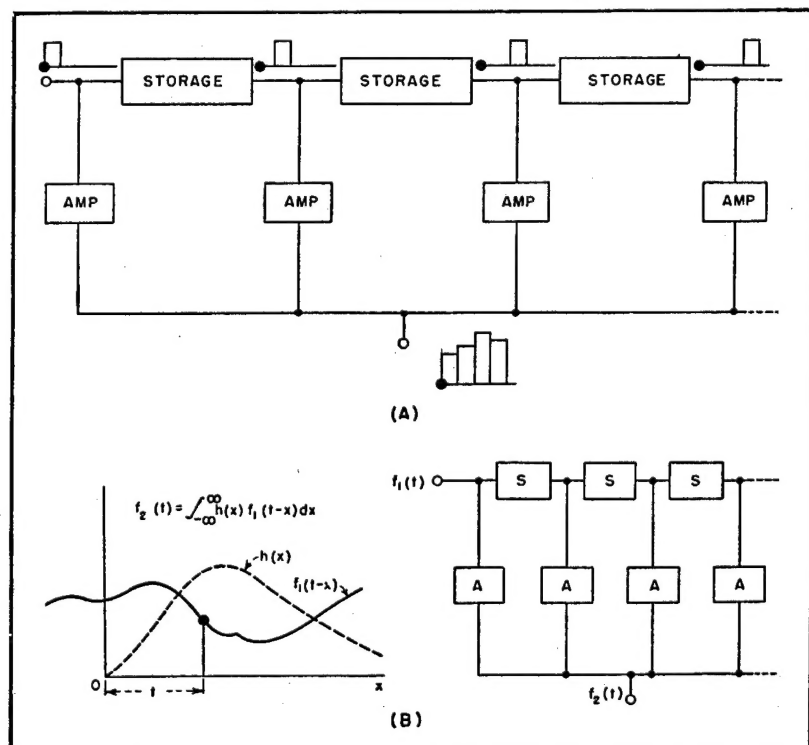


FIG. 1—A generalized linear network is adjusted as shown at (A) and operates in the manner indicated in (B)
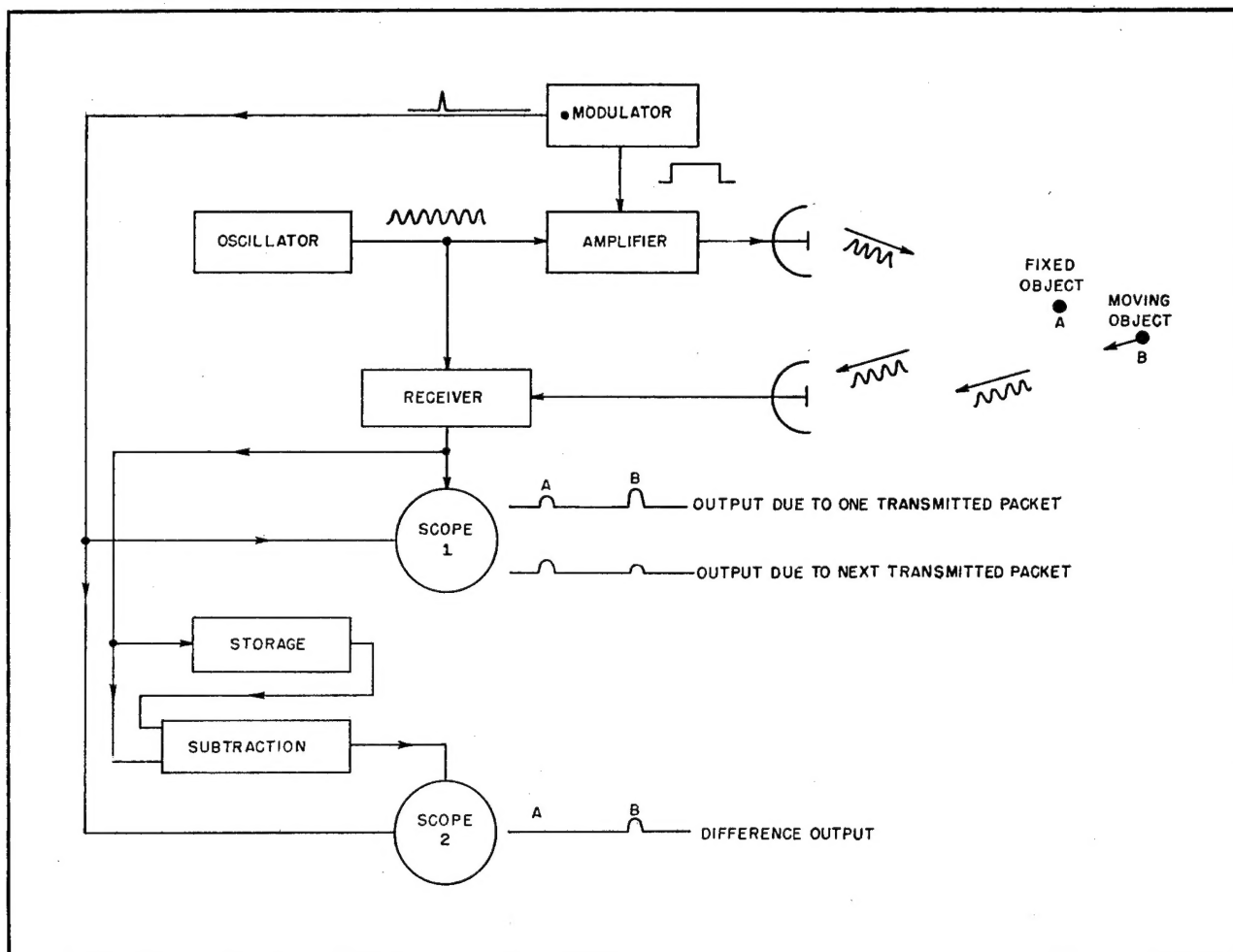
FIG. 2—Representative mti radar system. Scope 1 shows all targets while only moving targets are shown in scope 2

as these. The following examples will make evident the types of storage that are required in communications applications.

### Networks

In connection with a current investigation of optimum linear filters[1], there has been developed a generalized network that can be used to synthesize linear transfer characteristics experimentally. The network, based on the Wiener-Lee canonical form, is shown in Fig. 1A.

A transfer characteristic is synthesized, in the time domain, by adjusting the network to approximate the corresponding response to a unit impulse. The adjustment is performed by applying a narrow pulse to the input and setting the amplifiers to give the desired response. The first amplifier passes the input pulse, and hence affects the amplitude of only the first output pulse. The second amplifier

passes the pulse emerging from the first storage unit, and affects the amplitude of the second output pulse only. Similarly, each of the succeeding amplifiers is used to control the amplitude of an output pulse.

Once adjusted, the network responds to an input $f_1(t)$ by a process that is analogous to the graphical evaluation of the convolution integral. This analogy is illustrated in Fig. 1B. In the network, the variable $x$ of the integral may be thought of as representing distance toward the right. The weighting function $h(x)$, which is the response to a unit impulse, is contained in the amplifiers by virtue of the initial adjustments. The scanning function $f_1(t-x)$ is contained in the storage units; it may be visualized as a space plot of the voltage distribution along these units. Each amplifier multiplies corresponding points on the

weighting and scanning functions, and the mixed amplifier outputs represent the value of the integral at the particular time $t$.

This network is an example of a system in which the storage and weighting functions are separated. Furthermore, it demonstrates the necessity for a component whose only function is storage. The requirements that the storage component must satisfy are, in this case, particularly simple. Each storage unit is required only to deliver, at a later time, a replica of its input. The simplest storage device possessing this property is a delay line. Consequently, a tapped delay line will serve as the storage component of the network.

Another interesting application of delay-type storage is found in recent work that has been done on nonlinear systems[2]. A method has been formulated for characterizing nonlinear transducers, and a canon-

INPUT

STORAGE
CHANNEL 1

| 0 | 1 | 0 | 0 | 1 | 1 |
| 1 | 0 | 0 | 1 | 0 | |

CONTROL

STORAGE
CHANNEL 2

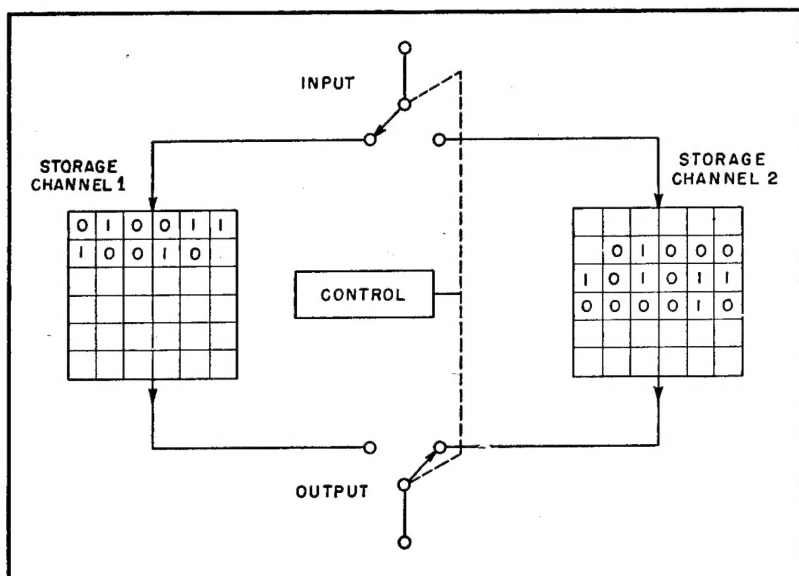| | 0 | 1 | 0 | 0 | |
| 1 | 0 | 1 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 | 1 | 0 |

OUTPUT

FIG. 5—Representation of a practical flexible storage system

original message. Storage units that function in essentially the same way as at the transmitting end are necessary, since again the time scale must be altered.

The statistical structure of most practical messages is much more complicated than that of the simple message in the preceding example. Practical messages are made up of more than two basic symbols. Also, the state of any particular symbol is affected by one or more preceding symbols. In a written message, for instance, it cannot be assumed that the occurrence of a certain letter is independent of all other letters. Rather, the fact must be considered that certain letters are more likely to occur when preceded by other particular letters, as in the combinations TH and ES. In speech, similar relations exist among the vowel and consonant sounds. In a television image, the light intensity of a particular spot is related to the intensities of other spots, both in the same and in preceding frames. The advantages of recoding can be realized in these more complicated cases. The detailed method of accomplishing the recoding will, of course, be quite complex. But, the fact remains that if recoding is to be carried out, alterations of the time scale are necessary. Highly flexible storage systems must be used at both the sending and receiving ends of the transmission system.

Most existing storage devices are capable of storing only binary pulses—pulses that can have only two states, and which can represent the binary digits of 1 and 0. This condition is not a drawback as far as the communications applications of storage are concerned. Information can be represented to any desired degree of accuracy by a sequence of binary numbers, and can therefore be electrically represented by binary pulses.

### Suitable Systems

A symbolic representation of a practical storage system sufficiently flexible to be used in communications applications is shown in Fig. 5. It is assumed that the information to be stored has been put in binary form.

If alteration of the time scale of the input is to be obtained, use of delay-line-type storage devices is not practical. A storage device should be used that preserves the state and order, but not the time relationship, of stored pulses. Such a storage device might be visualized as a box partitioned into a number of compartments. Incoming symbols are dropped into successive compartments, where they remain until removed by an external device; the rate at which this device operates determines the time relationship of the output symbols. In a practical storage system, it is preferable to have two storage

channels of this type, which are arranged as shown in Fig. 5. Incoming pulses are routed to one of the two channels, while pulses that were previously stored are being removed from the other. A control component automatically switches both the input and output connections when the channel from which pulses are being recovered is empty. It is seen that a continuous flow of information will be maintained through the system, but the operations of storage and recovery will never take place simultaneously in one channel. Circuit complexity is reduced because of the latter condition.

Two existing storage devices are suitable for use in a storage system of this general type—flip-flops and electrostatic storage tubes. Economically, the tubes are preferable because several hundred of the compartments shown on the diagram can be provided by one tube; a high-capacity flip-flop storage system is not practical because one flip-flop is required for each storage compartment. From the speed standpoint, flip-flops are better; electrostatic tubes now available cannot be operated as fast as flip-flops.

At this laboratory, construction of a two-channel electrostatic-tube storage system has recently been completed[5]. Each channel comprises one tube, and at present has a capacity of 256 pulses. For reliable operation, the required minimum time intervals between adjacent pulses are 30 microseconds when pulses are stored, and 15 microseconds when stored pulses are recovered.

The writer gratefully acknowledges the suggestions of R. M. Fano, J. B. Wiesner, H. E. Singleton, and C. A. Stutt.

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ical form developed for a large class of such transducers that comprises a finite number of resistors, capacitors, inductors, and rectifiers. In the canonical form, the storage function of the transducer is placed in evidence as a tapped artificial delay line; weighting alone is accomplished in the remainder of the network.

### Radar Applications

In a moving-target-indication (mti) radar system, a display is presented in which moving objects show up but stationary ones do not[3]. Such a display is obviously desirable when moving objects must be detected in a background of fixed objects. Storage components are essential elements of all mti systems.

The operation of such a system is illustrated by the simplified diagram of Fig. 2. The radar set sends out a pulsed oscillation that is reflected by various objects in its path. Received wave packets and the oscillator signal are mixed and detected, and an output is obtained that depends on the relative phase between the oscillator signal and each received packet. The phase relationships are functions of the distances between the radar set and the objects. The output due to a single transmitted packet is shown by the upper trace at scope 1; the first pulse is caused by object A and the second, by object B.

The output obtained when the next packet is transmitted is shown by the lower trace at scope 1. The pulse due to a fixed object such as A will be the same as before because the phase relationship between the oscillator signal and the reflected packet will not change. However, the pulse due to a moving object such as B will be different, since the change in the distance between it and the radar set will cause a change in the phase of the received packet with respect to that of the transmitted packet.

It is evident that response to fixed objects may be eliminated by subtracting the outputs due to two successive transmitted packets. In the subtraction process, the constant outputs corresponding to fixed objects will cancel, while the varying outputs corresponding to

moving objects will not. The cancellation obviously cannot be accomplished without the use of storage, since the output due to each transmitted wave packet must be preserved for a time equal to the interval between successive packets.

Packets are transmitted periodically. Consequently, a delay line having a delay time equal to the packet period will serve as the storage device. If delay-line storage is used, the receiver output and the delay-line output are combined in a subtraction circuit, which gives the difference output corresponding to two successive transmitted packets. This output is shown at scope 2.
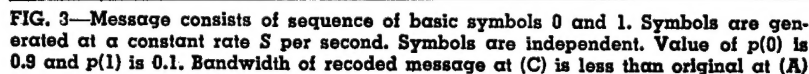
In place of a delay line and subtraction circuit, a suitable electrostatic storage tube can be used. When a spot on the target of such a tube is bombarded by the electron beam the spot is charged to a certain potential and stays at this potential for a short time. An output signal is obtained from the tube only when an uncharged spot is being charged. If a storage tube is substituted for the oscilloscope tube at scope 1, the mti difference output will be obtained directly. There will be no output corresponding to object A because any two successive traces on the storage-tube target will coincide everywhere except in the interval corresponding to a moving object.

### Recoding Messages

Possibly the most important communications application of storage is found in the problem of obtaining more efficient utilization of communication facilities. Although little work has been done on this problem in the past, an intelligent attack can now be made using information theory as a tool.

Quantitatively, the amount of information conveyed by an event depends on the logarithm of the reciprocal of the probability of the event. An event that is quite likely to happen conveys very little information when it does happen, whereas one that is unlikely to happen conveys considerable information when it happens.

In most communication processes, information is generated at a variable rate. The communication channels, however, are presently designed to transmit the information at the maximum rate at which it is generated. Consequently, the channels are not used in the most efficient manner. Reduction of the necessary bandwidth, or reduction of the average power required, or improvement of the signal-to-noise ratio, can be obtained by requiring the channels to transmit information at the average rate of generation, rather than at the maximum rate. These benefits cannot be obtained without the use of storage systems.

The basic method of smoothing the flow of information may be illustrated by a simple example. Suppose that the message to be transmitted is represented by a combination of two basic symbols, 0 and 1, which are generated at a uniform rate of $S$ symbols per second. Suppose, further, that the



FIG. 3—Message consists of sequence of basic symbols 0 and 1. Symbols are generated at a constant rate $S$ per second. Symbols are independent. Value of $p(0)$ is 0.9 and $p(1)$ is 0.1. Bandwidth of recoded message at (C) is less than original at (A)

symbols are independent, and that on the average 0 occurs nine-tenths of the time and 1 occurs one-tenth of the time. Such a message is shown in Fig. 3A.

The message may be represented electrically by a train of pulses that occur at a rate $S$ per second, and which have two distinct states, corresponding to the two symbols. As shown in Fig. 3A, the symbol 1 may be represented by a positive pulse and the symbol 0 by absence of the pulse that would normally occur at that time. Knowledge of the pulse repetition rate and indication of the symbol 1 are sufficient to specify the message, since it is known that the symbols occur at that rate and each must be 1 or 0.

The required bandwidth of the transmission channel will be determined by the maximum number of pulses per second which it must carry. If the representation of Fig. 3A is used, the channel must be capable of carrying pulses at the rate of $S$ per second, because it is possible, although very unlikely, that a sequence of 1's will appear somewhere in the message.

Now, suppose that instead of a pulse position being assigned to each symbol, a group of pulse positions is assigned to a group of symbols. If, for example, the symbols are taken in groups of two, as shown in Fig. 3B, four different group combinations will exist. The frequencies with which the groups occur will be different, because the symbol 0 occurs in the message more often than the symbol 1. To each group is assigned a different electrical representation. These representations are chosen in a systematic way that takes into account the relative frequencies of the groups. Representations of the more probable groups contain fewer pulse positions than those of the less probable groups[4].

The recoded message is shown in Fig. 3C. The pulses representing this message are also transmitted periodically. However, the repetition rate of these pulses is made less than $S$ per second because on the average, the recoded message will contain fewer than $S$ pulses per second. The latter fact can be seen by considering the group probabilities and representa-

tions of Fig. 3B. On the average, group 00 occurs 0.81 of the time, and occupies one pulse position; group 01 occurs 0.09 of the time, and occupies two pulse positions; and so forth. A simple calculation shows that an average of 1.29 pulse positions per group are required. In the original representation (Fig. 3A), however, two pulse positions per group were required. Consequently, the recoded message can be transmitted at a rate of $1.29S/2$ pulses per second. With this lower rate, a proportionate saving in channel bandwidth can be obtained. The use of longer groups, instead of just two-symbol groups, will generally result in a greater rate reduction.

It is seen that the flow of the information contained in the message has been smoothed out by the recoding. The more probable groups, which convey small amounts of information when they occur, are transmitted in shorter time intervals than the less probable groups, which represent larger amounts of information. This smoothing process is evidenced as an accordion-like compression and expansion of the time scale of the original representation. Recoding cannot be accomplished unless storage units are used. Without storage units, the necessary alterations in the time scale of the original message cannot be obtained.

The recoding may be carried out as shown in Fig. 4. The original message is routed to a small temporary storage unit, which has a capacity of two pulses. This unit may comprise either flip-flops or a tapped delay line. As soon as two pulses have been stored, the coder is actuated and generates the corresponding group representation,

which is placed in the main storage unit. Pulses are removed from the main storage unit at a uniform rate and are transmitted.

Pulses enter the main storage unit at a variable rate, but are removed at a constant rate. On the average, the unit will be half full, since the output rate equals the average input rate. From time to time, however, the number of pulses stored will vary. Suppose, for instance, that the unit is half full, and that a long sequence of 0's occurs in the message. Under this condition, stored pulses will be removed faster than new pulses enter. If the sequence of 0's is long enough, the storage unit will be emptied and the transmission system will temporarily fail. Alternatively, suppose that the unit is half full and that a long sequence of 1's occurs in the message. In this case, new pulses will enter the unit faster than stored pulses are removed, and if the sequence is sufficiently long, the unit will be completely filled. On the basis of the group probabilities, the capacity of the storage unit can be found such that the probability of failure of the transmission system has a specified value. This probability of failure can be made smaller by increasing the capacity of the storage unit, but it can never be reduced to zero as long as only a finite amount of storage is available. In practice the probability of failure due to overloading of the storage unit need not be made zero. It is sufficient to make this probability comparable to the probability of failure due to other causes.

At the receiving end of the transmission system, the inverse process of decoding the groups must be carried out in order to obtain the
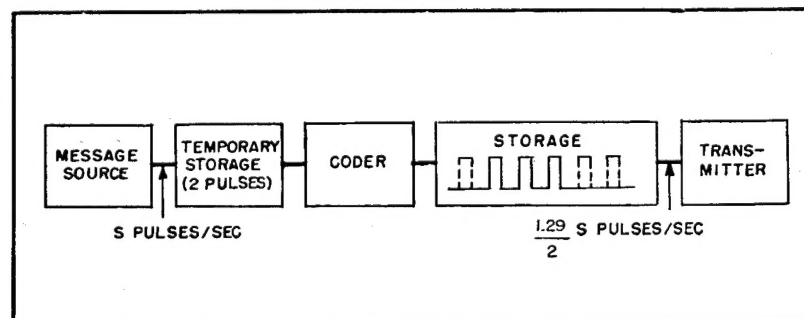


FIG. 4—Method of accomplishing recoding of Fig. 3